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SOLAR NEUTRINOS AND THE INFLUENCE OF RADIATIVE OPACITIES ON SOLAR MODELS

T. R. CARSON, D. EZER, AND R. STOTHERS
Institute for Space Studies, Goddard Space Flight Center, NASA
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ABSTRACT

Use of new radiative opacities based on the hot Thomas-Fermi model of the atom yields a predicted solar neutrino flux which is still considerably larger than the flux observed in Davis's ^{37}Cl experiment.

Subject headings: interiors, solar — neutrinos

The solar neutrino problem is still with us. However, it is well known that the predicted neutrino flux from the Sun is sensitive to the radiative opacity, and one obvious desideratum is "definitive" opacities or, in lieu of that, reliable upper and lower limits to the opacity. Carson (Carson and Hollingsworth 1968; Carson, Mayers, and Stibbs 1968) has pointed out that opacities based on the Thomas-Fermi and hydrogenic models of the atom, respectively, may serve as the desired upper and lower limits. It is found that solar models constructed with opacities obtained by applying scaling factors derived from the original Thomas-Fermi opacities of Carson *et al.* (1968) predict large neutrino fluxes (Stothers and Ezer 1973), while models built with hydrogenic opacities (notably those of Cox and Stewart 1965, with numerous subsequent modifications) predict neutrino fluxes (e.g., Ezer and Cameron 1971; Bahcall *et al.* 1973) that are still at least 5 times larger than the upper limit measured in the most recent ^{37}Cl experiment of Davis (1972 and private communication).

It seems to be of the greatest urgency to refine the computations of opacity based on the hot Thomas-Fermi atomic model, and this has recently been done by Carson (1974). The numerous improvements over the 1968 opacities will be described elsewhere, but we merely note here that hydrogen and helium are treated "exactly," i.e., with the help of accurate theoretical and experimental data; autoionization is justifiably (Merts and Magee 1972) neglected; electron-correlation and plasma dispersion effects are included; the Thomas-Fermi electron degeneracy parameter is the same for all atoms in the mixture, and the calculation of the electron occupation numbers ensures charge neutrality; and electron conduction is calculated by means of the Hubbard and Lampe (1969) code. The relative abundances of the metals have been taken from Cameron's (1973) recent compilation. The resulting opacities for solar conditions are found to be much closer to the hydrogenic opacities of Cox and Stewart (1965) than to the earlier Thomas-Fermi opacities when the same chemical composition is used for all three sets. However, all the opacities are sensitive to the adopted relative abundances of the metals, which differ in the various opacity tables actually used by constructors of solar models. This fact introduces an external source of error in all opacities.

TABLE 1

SOLAR NEUTRINO FLUXES ϕ (cm^{-2} s^{-1}) AT THE EARTH FOR SOLAR MODELS BASED ON THE NEW CARSON OPACITIES

Case	Normal Metals	No Metals
X	0.735	0.883
Z	0.015	0.000
α	2.0	< 0.1
X_c	0.45	0.59
T_c (10^6 ° K)	15.4	14.2
ρ_c (g cm^{-3})	137	121
log $\phi(pp)$	10.80	10.82
log $\phi(^7\mathrm{Be})$	9.54	9.11
log $\phi(^8\mathrm{B})$	6.79	5.98
log $\phi(^{13}\mathrm{N})$	8.61	...
log $\phi(^{15}\mathrm{O})$	8.53	...

In the present work, we have used the new Thomas-Fermi opacities to construct an evolutionary sequence of models for 1 $M_\odot$ up to the present Sun (whose age is assumed to be 4.5×10^9 years). Otherwise, the input physics is the same as in our previous work (Ezer and Cameron 1971; Stothers and Ezer 1973); in particular, the nuclear cross-sections are those of Bahcall, Bahcall, and Ulrich (1969), although we have here and elsewhere ignored the *pep* reaction. As before, we calculate the hydrogen abundance (X) and ratio of convective mixing length to pressure scale height (α) that yield the presently observed luminosity and radius of the Sun, for two values of subphotospheric metals abundance (Z).

The predicted neutrino fluxes are contained in table 1. For comparison with our earlier work, the collected results for the predicted neutrino capture rates at the Earth are given in table 2 (the unit is 1 SNU = 10^{-36} captures per second per target ^{37}Cl atom). The neutrino capture rates have been derived by multiplying the neutrino fluxes ϕ_i by the total capture cross-sections σ_i (Bahcall and Sears 1972) and summing the products.

From table 2 we find that the newly calculated Thomas-Fermi opacities yield predicted neutrino capture rates rather close to those yielded by the hydrogenic opacities, as was to be expected from our discussion above. The most recent hydrogenic opacities

TABLE 2

PREDICTED RATES OF CAPTURE OF SOLAR NEUTRINOS AT THE EARTH

Solar Radiative Opacities	Z	$\sum(\phi\sigma)$(SNU) all	$\sum(\phi\sigma)$(SNU) all but ^{8}B	Ref.
Modified Cox-Stewart......	0.015	6.4	1.2	1
Carson....................	0.015	9.8	1.4	3
Modified Cox-Stewart......	0.000	1.9	0.4	2
Carson....................	0.000	1.7	0.4	3

REFERENCES.—(1) Ezer and Cameron 1971; (2) Stothers and Ezer 1973; (3) present paper.

computed by the Los Alamos group for $Z = 0.02$ predict $\sum(\phi\sigma) = 4.8$–5.6 SNU (Bahcall *et al.* 1973), a result rather similar to ours for $Z = 0.015$. Even the drastic assumption that $Z = 0$ (or some very small value) below the photosphere yields a predicted neutrino capture rate about twice as large as Davis's current upper limit of 1 SNU, although Bahcall *et al.* (1973) obtained $\sum(\phi\sigma) = 1.4$ SNU for $Z = 0.002$.

We conclude that further improvements in the calculation of radiative opacities for solar conditions are unlikely to resolve the discrepancy with Davis's experimental results, if, as seems likely, the current hydrogenic and Thomas-Fermi opacities are reliable lower and upper limits to the "true" opacity.

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T. R. C. is on leave of absence from the Department of Astronomy, University of St. Andrews, St. Andrews, Scotland. D. E. is at present with the Department of Physics, Middle East Technical University, Ankara, Turkey.

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T. R. CARSON: University Observatory, Buchanan Gardens, St. Andrews, Fife, Scotland

D. EZER: Department of Physics, Middle East Technical University, Ankara, Turkey

R. STOTHERS: Institute for Space Studies, Goddard Space Flight Center, NASA, 2880 Broadway, New York, NY 10025